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TOUGH-FLAC COUPLED THM MODELING OF PROPOSED STIMULATION AT THE NEWBERRY VOLCANO EGS DEMONSTRATION

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ABSTRACT

In this study, we use the TOUGH-FLAC simulator for coupled thermo-hydro-mechanical (THM) modeling of the planned well stimulation for the Newberry EGS (Enhanced Geothermal System) demonstration. We analyze the potential for injection-induced fracturing and reactivation of natural fractures with associated permeability enhancement. More specifically, related to the design of the stimulation, our analysis aims at understanding how far the EGS reservoir may grow. We analyze the extent of the reservoir by studying the extent of the failure zone, using an elasto-plastic model and accounting for permeability changes as a function of the induced stresses.

INTRODUCTION

In 2009 the U.S. Department of Energy's Geothermal Technology Program awarded a grant to AltaRock Energy to demonstrate an Enhanced Geothermal System (EGS) at Newberry Volcano, Oregon. During Phase I of the project, completed in April 2012, pre-stimulation field investigations were performed to understand the tectonic and volcanic setting, characterize the volume around the proposed EGS demonstration area, and plan the stimulation parameters. A preliminary 3-D model of stress and fracture patterns by Davatzes and Hickman (2011) showed that faulting was mainly evident along the caldera rim about 3 km from the designated injection well, with no evidence (from drilling logs) of ring fractures or faults in the injection well (NWG 55-29). Furthermore, Newberry Volcano was found to have a very low seismicity rate; a much-improved seismic network installed in 2011 detected just two events (M 1.0 and 1.5) over approximately 1 year of monitoring (http://www.pnsn.org/volcanoes/newberry#). An analysis of the natural fractures there showed that there are two dominant sets that strike N-S and dip approximately 50° to the east and west (Davatzes and Hickman, 2011).

Modeling of the stimulation by Cladouhos et al. (2011) using the AltaStim simulator showed that it was possible to reach the EGS reservoir length goal (greater than 500 m), with the most attractive model reservoirs resulting when the pressures were well into the hydroshearing regime and just below the hydrofracking or tensile failure regime. Here, we compare those results with our alternative TOUGH-FLAC THM analysis and perform a sensitivity analysis of some key parameters, such as the initial state of stress and the frictional angle for shear reactivation.

MODEL SETUP

We conduct a coupled thermo-hydro-mechanical (THM) analysis using the simulator TOUGH-FLAC (Rutqvist et al., 2002), based on the geothermal reservoir simulator TOUGH2 (Pruess et al., 1999), which models multiphase and multicomponent fluids in a porous medium, and the geomechanical code FLAC3D (Itasca, 2009), which models the stress changes induced by pressure and temperature. Following the approach of Rutqvist et al. (2010) for modeling the stimulation injection at the Northwest Geysers EGS Demonstration Project, we study

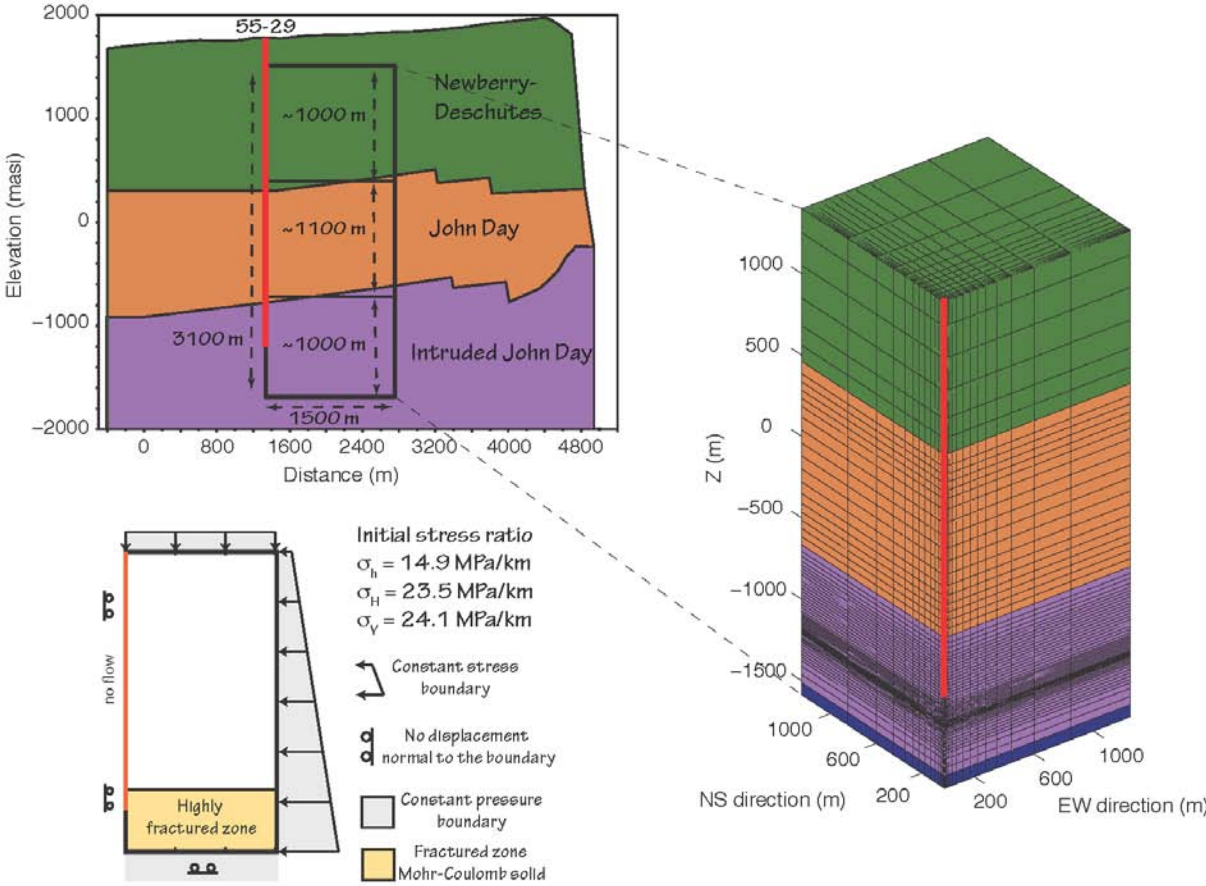

Figure 1. Mesh and boundary conditions for modeling stimulation at the Newberry EGS demonstration.

the stimulation at the Newberry Volcano. We consider a quarter symmetric model with injection well (NWG 55-29) located at one vertical edge (Fig. 1). The model consists of four layers, representing the main geological formations of the Newberry area (Sonnenthal et al., 2012). Hydrological properties are listed in Table 1. We assume a stress-dependent permeability (hence also an anisotropic initial permeability) with maximum permeability in the NS-direction, in order to simulate the highly fractured zone in the Intruded John Day formation at Newberry Volcano.

The injection well is divided into two parts, the first representing a cased well (high vertical permeability and very low horizontal permeability), and the second representing an open well allowing injection of cold water into the highly fractured zone. Pore compressibility (c_p) and thermal conductivity (λ) within the injection well are calibrated to match field data related to an injection test. Initial temperature and pressure distributions are extracted from earlier analyses of the prestimulation steady-state conditions at Newberry Volcano (Sonnenthal et al., 2012). The temperature follows a high gradient of ~100˚C/km, with a maximum temperature of about 315˚C at the bottom of the domain. The pressure is slightly lower than hydrostatic, with a linear gradient of about 8.3 MPa/km. Constant pressure is set at the top and bottom boundaries, whereas the side boundaries are assumed closed for fluid flow.

Mechanical properties follow the results by Li et al. (2012). We chose to simulate a homogeneous model using a Young's modulus E = 15 GPa and Poisson's ratio ν = 0.3. A homogeneous model should be adequate in this case, due to our short-term simulation (~3 weeks), which should affect only the injection zone (EGS reservoir). Geomechanical initial conditions follow those used by Cladouhos et al. (2011) for the AltaStim

Table 1. Hydrological properties. κ_i permeability along i-direction. ϕ porosity. ρ_{rock} rock density. D rock grain specific heat. λ thermal conductivity. c_p pore compressibility

	Newberry-Deschutes	John Day	Intruded John Day	Cased well	Open well
κ_x (m^2)	10^{-17}	$2.6\cdot10^{-16}$	$5\cdot10^{-18}$	10^{-20}	$5\cdot10^{-16}$
κ_y (m^2)	10^{-17}	$2.6\cdot10^{-16}$	$5\cdot10^{-17}$	10^{-20}	$5\cdot10^{-16}$
κ_z (m^2)	10^{-17}	$2.6\cdot10^{-16}$	$5\cdot10^{-18}$	10^{-8}	10^{-8}
ϕ (%)	10	5	3	95	100
ρ_{rock} (kg/m^3)	2400	2400	2400	-	-
D (J/kg ˚C)	1000	1000	1000	800	800
λ (W/m ˚C)	1.80	2.15	2.20	2.20	1.80
c_p (Pa^{-1})	$3.2\cdot10^{-9}$	$3.2\cdot10^{-9}$	$3.2\cdot10^{-9}$	-	-

simulation. We consider a vertical stress gradient of 24.1 MPa/km (σ_V, maximum principal stress on z-axis). The intermediate principal stress is oriented in the NS-direction (σ_H, y-axis), with a gradient of 23.5 MPa/km. Finally, the minimum principal stress is oriented in the EW-direction, with a gradient of 14.9 MPa/km (σ_h, x-axis).

Permeability changes

Changes in hydraulic properties may arise as the state of stress changes. In particular, the medium permeability is related to the fracture aperture b and the effective stress normal to the fracture σ_n, according to the following exponential function (Rutqvist et al., 2008):

$$b = b_i + b_{\max}\left(\exp(\alpha\sigma_n) - \exp(\alpha\sigma_{ni})\right) \quad (1)$$

where b_i is the initial aperture, $b_{\max}$ is the mechanical aperture corresponding to zero normal stress, α is a parameter related to the curvature of the function, and σ_{ni} is the initial stress normal to the fractures. In our formulation, compressive stresses are considered negative. Because Newberry Volcano features a NS-striking fracture system (i.e. y direction), we can calculate the changes in permeability along the y-direction (κ_y) as a function of the normal stress (σ_x), using the cubic law of parallel-plate flow (Witherspoon at al., 1980) and an approach for scaling the fracture properties with the initial permeability (Liu et al., 2004):

$$\frac{\kappa_y}{\kappa_{yi}} = \left[\frac{R_b + \exp(\alpha\sigma_x)}{R_b + \exp(\alpha\sigma_{xi})}\right]^3 \quad (2)$$

where the stress aperture function is related to the dimensionless parameter $R_b = b_r/b_{\max}$, where b_r represents the residual aperture. Using R_b, the permeability change factor is independent of initial permeability, and we need to calibrate our model using two parameters only (R_b and α; see following section).

Shear reactivation also enhances permeability changes—it is the main mechanism for generating permanent permeability enhancement within the EGS reservoir. In this work, we assume that permeability would change by a fixed factor if a gridblock is subjected to shear reactivation:

$$\kappa_i = K_{HS} \cdot \kappa_i^{bHS} \quad (3)$$

for the i-direction. K_{HS} is the constant value (set to 1 or 100 for the base-case analysis), and the index bHS refers to the permeability before the hydroshearing.

Model calibration

Model calibration was conducted by simulating an injection test and comparing the resulting pressure and temperature profiles along the well with data collected at well NWG 55-29 during a field injection test (September–October 2010).

According to Davatzes and Hickman (2011), the injection test was performed in two steps. The injection began for three days with an injection rate of 10 gpm (~0.63 kg/s) and temperature of 10˚C, and a wellhead pressure of about 5 MPa (750 psi), followed by a two-week shut-in. Then the injection restarted for nine days with an injection rate of 22 gpm (~1.4 Kg/s) and temperature of 10˚C, and a wellhead pressure of about 8 MPa (1153 psi).

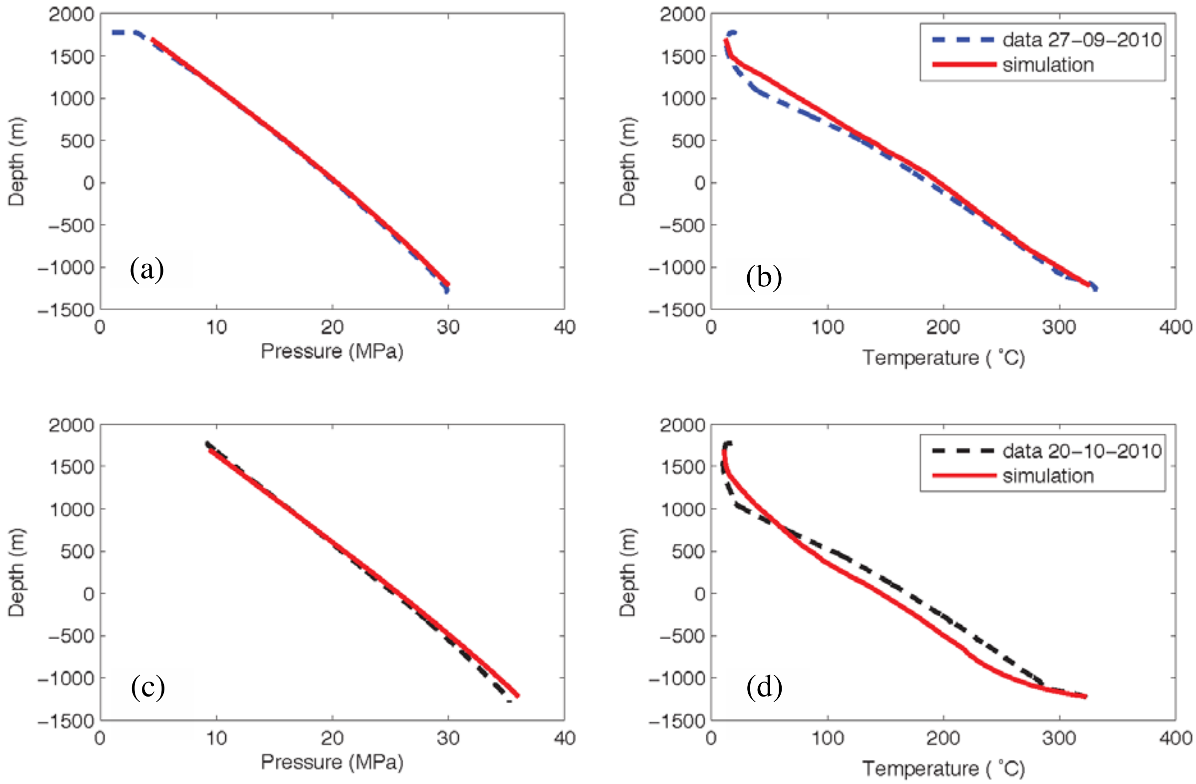

Figure 2. Model calibration. (a) Pressure well log (blue dashed line) and simulated pressure (red line) after 3 days (09/27/2010) of 10 gpm injection rate. (b) Temperature well log (blue dashed line) and simulated temperature (red line) after 3 days (09/27/2010) of 10 gpm injection rate. (c) Pressure well log (black dashed line) and simulated pressure (red line) after 9 days (10/20/2010) of 22 gpm injection rate. (d) Temperature well log (blue dashed line) and simulated temperature (red line) after 9 days (10/22/2010) of 22 gpm injection rate.

In our model, we aim to reproduce the same observed profiles along the well while considering permeability changes that might arise with the evolving stresses. The resulting profiles are shown in Figure 2. The parameters determining permeability changes are set to R_b = 0.2 and α = 0.13 MPa^{-1} (see Eq. 2). The pore compressibility and thermal conductivity are calibrated as well, to allow a good match between the simulated and measured profiles (Tab. 1). As stated by Davatzes & Hickman (2011), the pressure log after the nine-day 22 gpm injection was made with a lower well-head pressure; hence, the pressure field data in Figure 2d need to be recalibrated to match a wellhead pressure of 8 MPa (1153 psi).

STIMULATION MODELING

In the stimulation of the Newberry EGS system, at most 24 million gallons are expected to be injected into at least three separate zones or depth ranges (Cladouhos et al., 2012). The stimulation is planned for three weeks (21 days) —one week per zone, with a maximum injection rate of 800 gpm (about 50 kg/s) in each zone. However, in our stimulation modeling, we consider a fixed, high wellhead pressure of 16.2 MPa (2350 psi), rather than a constant rate of injection, following the simulation performed by Cladouhos et al. (2011, 2012).

To estimate the extent of the EGS reservoir in this case, we look at the zone where the system is subjected to hydroshearing. This can be done with a Mohr-Coulomb model; assuming a cohesionless solid, a shear reactivation will occur when the following criterion is respected:

$$\sigma'_{1c} = N_\phi \sigma'_3 , \quad N_\phi = \frac{1+\sin(\phi)}{1-\sin(\phi)} \tag{4}$$

where σ'_{1c} is the critical maximum principal effective stress (σ'_V or σ'_{zz} in our case), and σ'_3 is the minimum principal effective stress (σ'_h or σ'_{xx}). ϕ is the frictional angle (with frictional

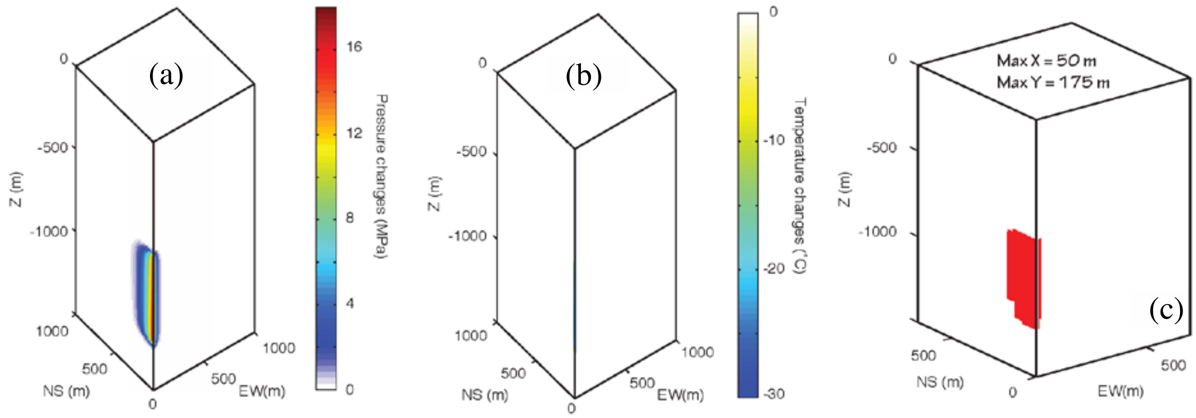

Figure 3. Simulation results for the base case simulation without shear-enhanced permeability after a stimulation 21 days long at constant wellhead pressure (16.2 MPa). (a) Resulting pore pressure changes. (b) Resulting temperature changes. (c) Resulting hydrosheared zone. Without considering shear-enhanced permeability, the shear reactivation occurs up to about 200 m from the injection well in the NS-direction.

coefficient $\mu = \tan\phi$), which is set to 30˚ for the base-case simulation.

Equation 3 corresponds to the case in which the fractured media with fractures of any orientation exist at every location. However, in the case of the anisotropic stress field at Newberry Volcano, east and west dipping, pre-existing fracture planes will most likely hydroshear, resulting in permeability enhancement in the subvertical and NS directions. Using this approach, shear reactivation would be induced whenever the maximum principal stress is N_ϕ times higher than the minimum principal stress.

Base case

The first model we analyze does not take into account permeability changes owing to hydroshearing (i.e., K_{HS} = 1 in Eq. 3). Figures 3a and b show the resulting changes in pressure and temperature, respectively, within the EGS reservoir after 21 days of stimulation. The pressure perturbation spreads out between 300 and 400 m from the injection well in the NS-direction, while it is confined along the EW-direction (spreading less than 100 m). The injection produces pressure changes at the reservoir depth up to about 18 MPa around the well. The temperature variation is mostly confined around the injection well, and extends only a few meters, with changes up to more than 100ºC (scale in Figure 3b is saturated at 30ºC).

Figure 3c shows the resulting extent of the EGS reservoir for this base case. The red zone in the figure represents the region where hydroshear reactivation has occurred. In this case, the hydrosheared zone extends about 200 m in the NS-direction (strike direction of the fracture system). In the EW direction, on the other hand, the EGS system is quite confined, extending only about 50 m. The total water flux calculated after 21 days of stimulation is about 2.5 million gallons. These values are not in agreement with the analysis performed with the AltaStim software, which predicted, with the prescribed wellhead pressure of 16.2 MPa, an EGS length greater than 500 m and a total volume of about 22 million gallons (Cladouhos et al., 2011).

Base case with shear-enhanced permeability

In this section, we assume that hydroshearing will affect permeability by up to two orders of magnitude when shear reactivation takes place. Enhanced permeability allows the pressure perturbation to propagate further into the reservoir. As shown in Figure 4a, the pressure perturbation extends to between 800 and 900 m in the NS-direction and up to 200 m in the EW-direction. In this case, injection produces pressure changes of up to 10 MPa around the well. Although the temperature changes are still mostly confined to the injection well, the enhanced permeability permits the temperature to decrease up to 50 to 100 m from the injection well, with changes up to about 30˚C (Fig. 4b).

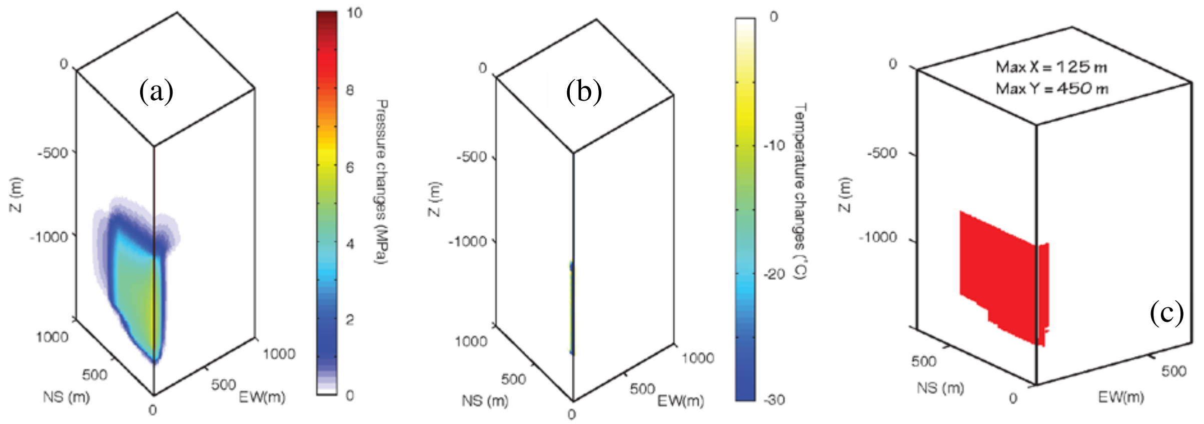

Figure 4. Simulation results for the base-case simulation considering shear-enhanced permeability after a stimulation 21 days long at constant wellhead pressure (16.2 MPa). (a) Resulting pore pressure changes. (b) Resulting temperature changes. (c) Resulting hydrosheared zone, with shear reactivation occuring up to about 500 m from the injection well in the NS-direction and 150 m in the EW-direction.

Figure 4c shows the resulting extent of the EGS reservoir for this case. Hydroshear occurs up to ~500 m from the injection well in the NS-direction, and up to 150 m in the EW-direction. In this case, the EGS reservoir extent is similar to that calculated using AltaStim, whereas the calculated total water injected is about 14 millions gallons, still slightly lower than the value found by Cladouhos et al. (2011).

SENSITIVITY ANALYSIS

In this section, the extent of the hydrosheared zone, and hence the extent of the EGS reservoir, will be analyzed as a function of two key parameters: (1) the factor for shear-enhanced permeability changes (K_{HS} in Eq. 3), and (2) the frictional angle (ϕ in Eq. 4).

Figure 5 shows the zone where shear reactivation occurred for three different values of the shear-permeability enhancing factor. The region subjected to shear reactivation is directly proportional to this factor, i.e., the higher the permeability after hydroshearing, the larger the shear reactivated region. The extent of the EGS reservoir in the NS-direction varies from about 350 m for a factor K_{HS} = 10, to a value of 600 m when that factor is increased by several orders of magnitude (K_{HS} = 10000). The extent of the hydrosheared region in the EW-direction is about 150 m, independent of permeability-enhancing factor for the range considered.

In the base-case simulations, we previously used a very low frictional angle, which results in a friction coefficient of about 0.6, i.e., almost a critical value for the considered initial stress distribution. Assuming a lower value for the frictional angle (ϕ <30˚) would cause shear reactivation of the entire highly fractured zone (Fig. 1) under initial stress conditions (i.e., before the stimulation starts). For this reason, we studied values higher than 30° in our sensitivity analysis of the frictional angle.

Figure 6 shows the resulting EGS reservoir extent as a function of the frictional angle. The extent of the reactivated region in the NS-direction is inversely proportional to the frictional angle, varying from about 500 m in case of low angle (30º with frictional coefficient μ=0.6), to as short as 275 m for the highest considered angle (39º with frictional coefficient μ=0.8). The same inverse correlation is observed for the extent in the EW-direction, with the minimum value (about 30 m) resulting for the highest frictional coefficient.

CONCLUSIONS

In this paper, we report on the THM modeling of the proposed stimulation at the Newberry EGS Demonstration site in Oregon. Starting with previous results from the AltaStim software, and building on experience from the Northwest Geysers EGS demonstration Project,

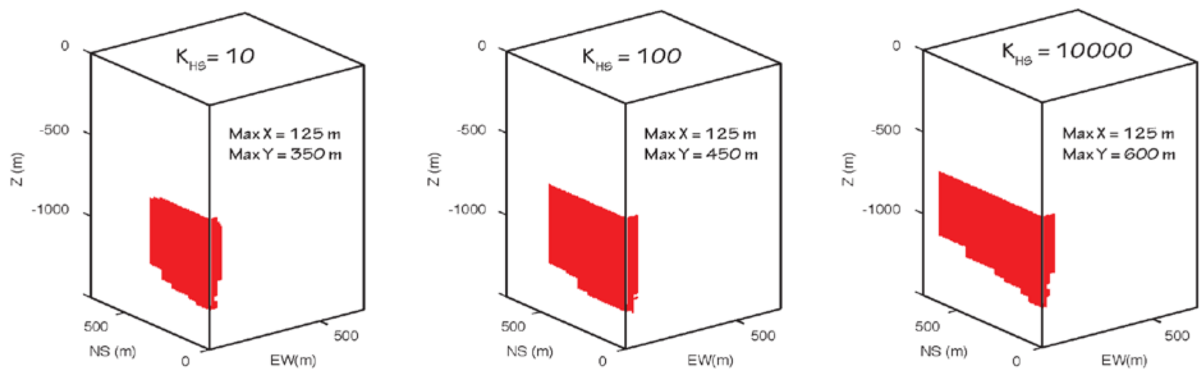

Figure 5. Sensitivity analysis results for the Mohr-Coulomb solid stimulation modeling, with the factor for shear-enhanced permeability given by (a) 10, (b) 100 (base case), and (c) 10,000.

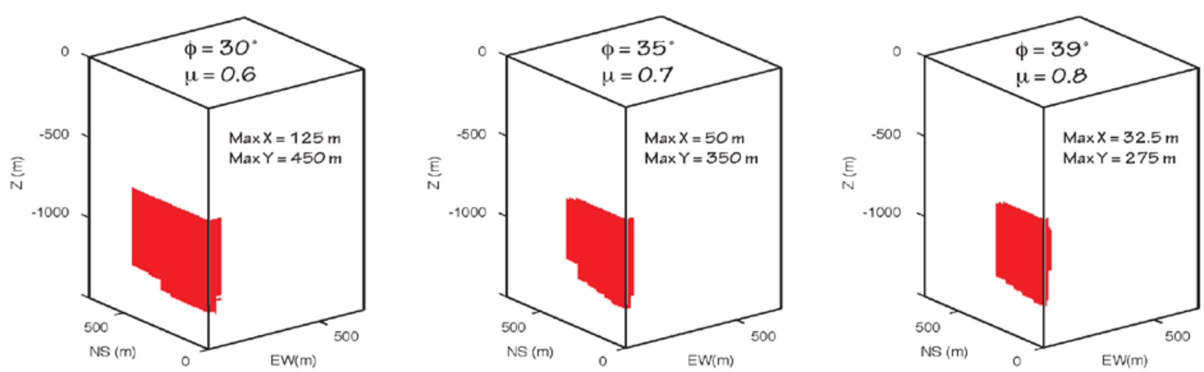

Figure 6. Sensitivity analysis results for the Mohr-Coulomb solid stimulation modeling, with the frictional angle given by (a) 30° (base case), (b) 35°, and (c) 39°.

we modeled the stimulation phase using the coupled TOUGH-FLAC code. Taking into account permeability changes that can result from stimulating a pre-existing NS-striking fracture system, we first calibrated our model by simulating an injection test and comparing the results with field data. Then we simulated a high-rate injection, fixing the wellhead pressure to the same value used previously with the AltaStim simulator.

Results show that shear-enhanced permeability has to be accounted for when hydroshearing occurs in order to reach the 500 m stimulation-zone goal. In all of the TOUGH-FLAC simulation cases, the total volume of injected water is less than that observed in the AltaStim simulation (Cladouhos et al., 2011). However, we did not consider shear-induced changes in porosity. In fact an enhanced porosity would tend to increase the water volume injected.

We also present a sensitivity analysis focusing on the extent of the hydrosheared zone as a function of the shear-enhanced permeability factor, and of the frictional angle. For values of the permeability factor that range over several orders of magnitude (and only for values greater than 10), the stimulated rock extent is very close to the target length of 500 m. Regarding the frictional angle, unless the system is close to a critical state (μ=0.6), the target length of 500 m is unlikely be reached.

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